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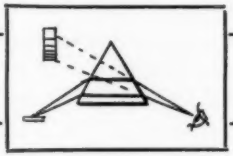

APRIL
1932

A METHOD OF PROJECTION IN RELIEF AND COLOR

By Herbert E. Ives
[Bell Telephone Laboratories, New York, New York
Received January 20, 1932]

For relief pictures of the parallax panoramagram[1] type to be most realistic and attractive, they should be in color. In the commercial production of these pictures, some success has been achieved by hand coloring the transparencies. This method is, however, very severely limited in its applicability. In general, those parts of the reproduced scene which are positioned anywhere except in the plane of the transparency, change their positions with respect to the transparency as the observing position shifts. Any layer of coloring material applied to the transparency will as a consequence move to different parts of the scene with the motions of the observer. In practice this objection has been met in part by restricting the picture to objects lying in the picture plane, with simple backgrounds, such as draperies or flat walls, and by limiting the angle through which the picture is taken and viewed. These are however undesirable compromises and other methods of introducing color, not subject to such limitations, are desirable.

In relief pictures in the form of transparencies, it is possible to imagine the introduction of color by utilizing one of the screen plate meth-

[1] For a description of this kind of relief picture see J.O.S.A: *A Camera for Making Parallax Panoramagrams, 17*, #6, December, 1928. *Parallax Panoramagrams for Viewing by Reflected Light, 20*, #10, October, 1930. *Parallax Panoramagrams Made with a Large Diameter Concave Mirror, 20*, #11, November, 1930.

ods of color photography. In order to preserve to the fullest measure the fine detail in the minute panoramic strips, the most desirable form of screen plate process would be one of those, such as the Joly, in which the three-color elements are in narrow adjacent strips, which for this purpose should run at right angles to the panoramic strips and the grating or ridged structure required for relief purposes. So far as I am aware no experiments have actually been made on the production of panoramagrams using screen plates for the introduction of color. Such a development appears entirely feasible, although the resultant pictures would be quite expensive and would require very intense illumination to offset the large losses in light occurring in both the color process and in the opaque line grating ordinarily used for relief pictures. The problem of making duplicate copies is also a serious one.

In surveying the various exemplifications of the three-color process, we find that there is one which has reached its most practical development when utilized in *projection*. This is the process in which the three-color records are embodied in fine adjacent strip images which are directed by a ridged structure adjacent to the picture into three colored apertures of a projection lens. This principle, first proposed for an instrument termed the "chromolinoscope,"[2] has lately been commercialized in the Kodacolor film process. Recently, I have described methods for projecting parallax panoramagrams upon several forms of special screen, thereby achieving projection in relief.[3] In working out the details of these projection methods, it has developed that the problem of introducing color into relief pictures is rather elegantly solved by a combination of these projection methods with the chromolinoscope idea. A description of the various steps in a method for doing this follows:

The method of projecting pictures both in relief and color, in so far as the final projection operation is concerned, is a straightforward combination of the Kodacolor scheme with the relief projection methods already described. Thus in Fig. 1, which is reproduced from an earlier paper, S is the translucent screen built up of transparent rods having appropriate different curvatures on their front and back surfaces. The picture to be projected is placed in the projection lantern P and consists, in so far as it is a record of relief, of narrow panoramic strips which are accurately focused upon the rear ridges of the screen S. In order to introduce color, it is only necessary that the picture, in addition to carrying the panoramic strips, shall carry color record strips in sets of three

[2] F. E. Ives, U. S. Patent 666,424, Jan. 22, 1901.

[3] *The Projection of Parallax Panoramagrams.* J.O.S.A., *21*, (7), 397; July, 1931.

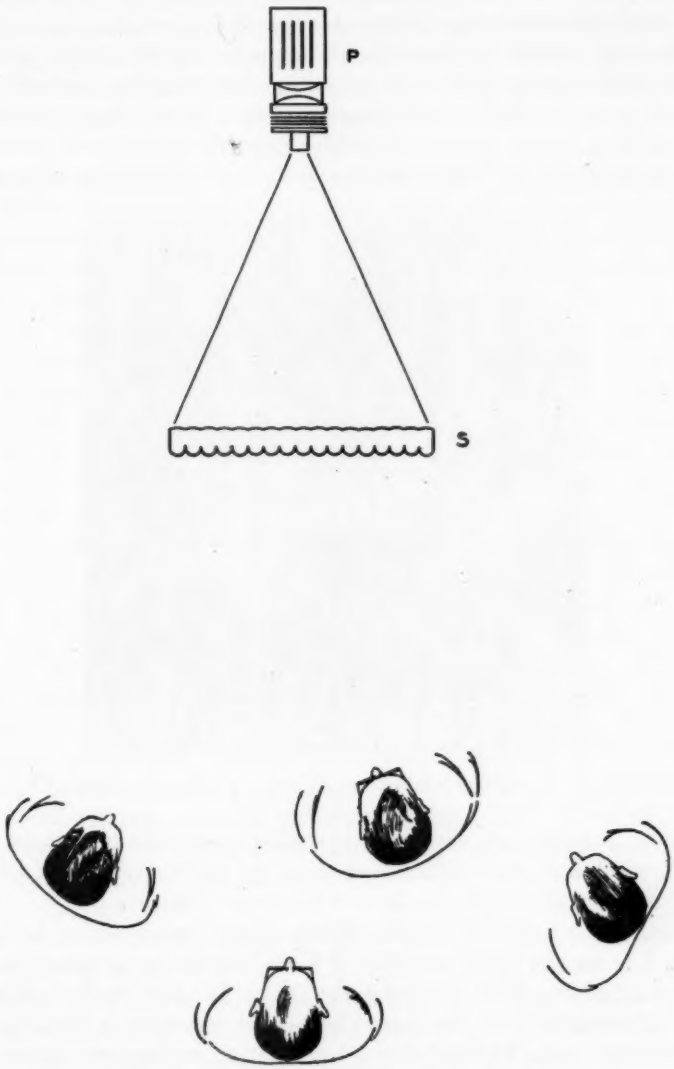

FIG. 1. *Method of projecting parallax panoramagrams.*

placed closely behind a ridged or other structure which shall image these strips onto three colored apertures in the projection lens. In order to avoid confusion and patterning between the panoramic strips and the colored record strips, these should be placed at right angles to each other and the apertures in the projection lens should be horizontal instead of vertical as is usually the case. Fig. 2 shows diagrammatically the structure of the picture which is required for this purpose. The relatively wide vertical strips with their mottled images are the panoramic

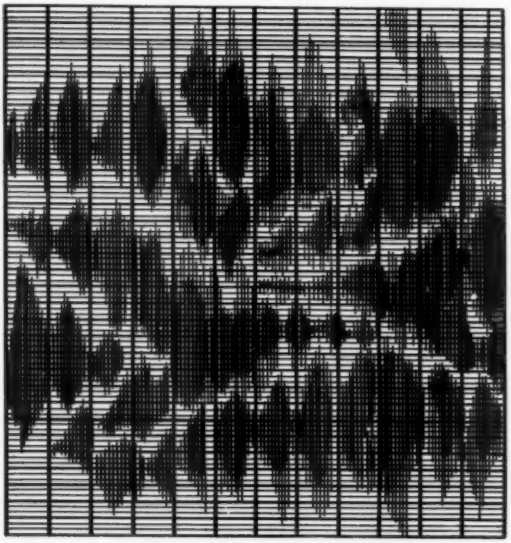

FIG. 2. *Structure of picture embodying records of both color and relief.*

records, and the very narrow horizontal strips are the three-color records, which are covered, in sets of three, by the convex ridges necessary to image them upon the back of the projection lens.

Assuming a picture as just described available for projection, we have a black and white record carrying all of the information necessary to reconstruct an image in both relief and color. The medium for utilizing this information is, in the case of both relief and color, a structure of cylindrical lenses. The cylindrical lenses for recovering the element of relief are in the ridged projection screen, and the cylindrical lenses for recovering the element of color are in the picture or "slide" placed in the lantern.

The problem of producing the relief and color record shown in Fig. 2 may be solved by introducing the chromolinoscope principle into one of the various forms of cameras which have been used for making parallax panoramagrams. I shall, however, describe only one method, which is in many respects the simplest and most attractive, in that the record is made by a single exposure with apparatus involving no moving parts. This method utilizes a large concave mirror for viewing the object through a wide angle, and the special features over and above those previously described are those necessary to introduce the color records and to produce an image of a size for use in a practical projection lantern.

The complete apparatus is shown diagrammatically in Fig. 3. The light from the object O passing to the strip concave mirror C, is reflected back to the semi-transparent mirror M standing at 45°, and from it downward to form an approximately full sized image at I. In the process of making ordinary parallax panoramagrams, an opaque line grating is placed at this point, and a sensitive plate separated by a small interval receives the little panoramic images developed behind each grating space. For projection purposes, an image in natural size, which in the case of a face would require a plate of approximately $10'' \times 12''$, is not suitable for use in a projection lantern of ordinary size. Accordingly it becomes necessary to reduce the image thus formed to convenient size. This cannot be done by the expedient which would perhaps occur first to the photographer, of moving the object to a much greater distance, for the reason that with the object at a greater distance the concave mirror would subtend only a small angle and the final picture would be visible in correct relief through a correspondingly small range. What is required is a straight photographic reduction of the image formed behind the grating at I. This may be done by making a reduced copy of the large negative as ordinarily obtained, but it is preferable to save operations by photographing the panoramic images as formed on a ground glass at I by means of a lens L_2 on to a sensitive surface F of the required size.

In place of photographing the panoramic images as received on a ground glass, as just suggested, it is preferable, from the standpoint of light gathering power, to substitute for the grating some form of transparent ridged screen. This screen may carry either convex ridges or concave ridges, forming respectively real or virtual panoramic strips, the exact type of screen being dictated by the kind of projection screen to be used. For the convex ridged projection screen which is shown in Fig. 1, it is necessary, in order that the final projection shall be stereoscopic

and not pseudoscopic, to use a screen of concave ridges in the camera as indicated in Fig. 3. One further optical element which is necessary, is a large convex lens L_1 placed in contact with the screen S, of such focal length as to image the concave mirror C in the image forming lens L_2.

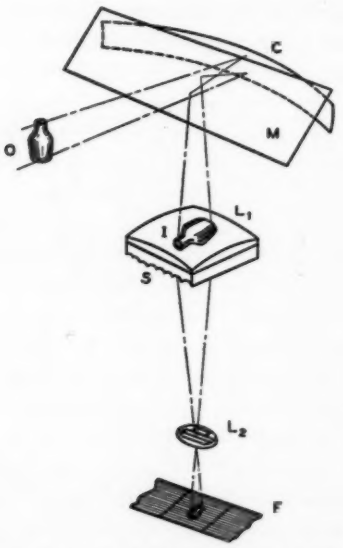

FIG. 3. *Apparatus for making photographs for projection in relief and color.*

Proceeding now to the elements necessary to form the three color records, we introduce over the lens L_2 three colored apertures of the sort used in the Kodacolor camera, and we use as our photographic recording means at F, a ridged sheet backed by a photographic sensitive layer. The relative dimensions of the aperture system over the lens L_2 and the concave mirror strip C must be so chosen with respect to the focal length of the large lens L_1 that the apertures at L_2 are uniformly and completely filled with the light from the mirror. The convex ridges at F must, of course, be of such curvature that at the working distance between the lens L_2 and F, the three apertures are imaged as closely adjacent strips, the final image conforming as closely as possible to the arrangement shown in Fig. 2. The ridges above the sensitive surface and the apertures in the lens L_2 must, of course, as already mentioned, lie at right angles to the concave ridges of the screen S, and the photographed images of it on F.

An experimental demonstration of this idea, in so far as the element of relief projection is concerned, has been found feasible. For this purpose, a spherical concave mirror of four feet diameter and four feet radius of curvature, (actually built up out of three 16″ mirrors placed side by side) has proved entirely successful. For the concave ridged screen at S, a sheet of thin celluloid has been used which has been prepared by wrapping it around a large drum and cutting the ridges on a lathe with a carefully shaped cutting wheel, the ridges being given a final careful polishing with felt. It has been found possible to give a reasonably good figure to these ridges when they are made as fine as 16 to the inch, or 160 across a 10″ sheet. The virtual panoramic images formed at this ridged screen have then been successfully photographed on to a lantern slide plate by the use of a high quality lens at L_2, sufficient detail being preserved in the 160 fine strips to produce images exhibiting relief on a projection screen of the type described in which the constituent rods are 1/4 inch in width.

When it comes to the element of color we know, without new experimentation, that the method proposed is practical, since it is already in commercial use. In proceeding to combine it with the relief projection method, a practical difficulty outstanding at the present time is that transparent ridged material backed by photographic emulsion is available only in the form of Kodacolor film, which suffers from two serious practical defects. The first is that the film now available, of 16 millimeters width, is altogether too small to carry an adequate number of the fine panoramic strip images with satisfactory resolving power. The second is that film is unsuitable for this purpose because of its tendency to introduce distortion through expansion, contraction and warping. For the present purpose, the extremely fine ridges of the Kodacolor film (600 to the inch) are much smaller than are necessary or desirable. Thus for lantern slide size, which is about as small as the panoramagram transparencies can be made for projection, the individual panoramic strips for the experimental apparatus which has been used run about 60 to the inch. Approximately the same sized ridges would be adequate for the color distributing ridges on the picture to be projected. With a projection lens of practical focal length, this means that the distance between the ridges and the photographic emulsion can be made comparatively large. These considerations lead to the conclusion that for this purpose, the picture for projection might very well be made upon a glass plate which could be prepared by molding or rolling glass of approximately ordinary lantern slide thickness. (The optical figure required in

these ridges, which form only three images, is much less perfect than that required in ridges for relief purposes.) The great advantage of the glass would be, of course, its freedom from warping. In addition, with structures of the size indicated, it would be feasible to make the lantern slides for projection by contact printing from the negative made in the camera, the simple registration process involved being carried out before printing by non-actinic light, or the print and the ridged structure could be on separate plates, to be mounted together to form the complete slide.

It is obvious that the method which has been outlined is, theoretically, capable of being developed into a method of *motion* picture projection in color and relief.[4]

[4] For a discussion of the difficulties encountered in applying the parallax panoramagram principle to motion pictures see *The Problem of Projecting Motion Pictures in Relief*, J. of the Soc. of Motion Picture Engineers, to appear shortly.

POLYCHROME PHOTOGRAPHY

By Frederic E. Ives
[Philadelphia, Penna. Received December 21, 1931]

It is not usual in a communication to a scientific journal to advocate a departure from strictly scientific and well proved methods of procedure; but the object of this communication is to show how in one case a sacrifice of theoretical accuracy can make the difference between success and failure in the popularizing of a beautiful art,—namely color photography.

Convincing and unsurpassable results were obtained in trichromatic color photography nearly half a century ago in the photochromoscope system "additive" process, and "subtractive" process transparencies and prints on paper followed, but the prints on paper which the layman demands, have always been by processes suitable for operation only by experienced experts. In consequence, they have never been widely popularized.

It has also been necessary to provide special and expensive cameras to produce three negatives with perfectly defined detail at a single exposure from a single viewpoint, and exceptional skill and experience are necessary to coordinate accurately a considerable number of factors which on account of often unavoidable variations in materials and atmospheric conditions necessitate modifications of adjustment and procedure.

By a most interesting scientific compromise, results which are accepted as fine examples of the most successful trichromatic process work are now obtained with only two negatives which are made on two plates in face-to-face contact in an ordinary plate camera, and two "gaslight" prints which when cemented together make a color photograph suitable for the album or framing.

The plates used are a green-blue sensitive plate, glass side towards the camera lens, and facing it in pressed contact a panchromatic plate. Action by the blue-violet spectrum rays is very nearly completely cut out on the front plate by means of a yellow color screen, and nearly all but the red-orange light action is cut off from the panchromatic plate by an imponderable surface dye stain on the face of the emulsion of either plate. This "bi-pack" can be exposed in an ordinary plate camera, and is "fast" enough to permit of "snapshot" exposures in direct sunlight.

The negatives can also be made on films, pressed in face-to-face con-

tact against a glass plate, and could be so made in a modified roll-film camera.

Up to this point, this is what is popularly known as a "two-color process," but although only two prints are made, one from each negative, three colors are used as in the ordinary trichromatic process, and the secret of success lies in the way in which these colors are automatically taken up and differentiated in the print-making process.

Otherwise, using only minus red (cyan blue) and red colors, as has been the common practice for the sake of simplicity and economy in subtractive process color motion picture production,—and assumed to be the correct practice in printing from the two negatives,—no foliage greens or orange and yellow fruits and flowers would be reproduced.

This limitation is now removed with no additional printing or procedure by making a dichroic red-to-yellow print (red in the deep shades, but shading down to orange and yellow in the very light shades), and superposing it on a chemically blue-toned bromide print from the red record negative. Separately, these two prints look most unpromising, but their combination effects a seemingly magical transformation.

Blue skies, foliage greens, red, orange and yellow fruits and flowers, brown, auburn and golden hair, brown and blue eyes, blond and brunette flesh tints, are differentiated with astonishing fidelity, and the results are altogether pictorially satisfactory.

The color print combination consists of a "blue-toned" ordinary bromide paper print from the panchromatic plate negative, and a print on Eastman positive film from the other negative, made by exposure through the carrier, developed to a black image and bleached to transparency in a bath which selectively hardens the gelatine, then developed in hot water and cleared in hypo to produce a tenuous colorless gelatine relief image which is colored up by immersion in a suitable dye bath. These prints can either be made by contact printing, or in an enlarging camera to any desired size.

The bromide paper print is converted to a clear pale cyan blue (minus red) color in a bath made preferably with ferricyanide of potassium, oxalic acid, potassium bromide, sodium chloride and sesquichloride of iron.

Water	15 oz.
Potassium ferricyanide	27 grains
Oxalic acid	54 grains
Sodium chloride	65 grains
Potassium bromide	32 grains
10% dilution of U.S.P. iron chloride solution	2 to 4 drams

If highlights of the bromide prints are at all overcast, the addition of a little potassium permanganate or potassium bichromate is advantageous.

The intensity of the cyan blue image is under perfect control by variations in the iron content of the toning bath, and a too heavy blueprint can be reduced to any extent by soaking in a borax solution, which should be followed by washing and immersion in extremely dilute sulphuric acid.

The silver image of the Eastman film transparency print is bleached and the gelatine selectively hardened in the following bath:

Water	15 oz.
Potassium bichromate	20 grains
Potassium bromide	80 grains
Glacial acetic acid	½ fluid ounce

It is then developed in hot water (100° F) to a tenuous gelatine relief, cleared in plain hypo solution, washed and dried. It is then dyed in a solution of carmoisine and metanil yellow dyes. The dye bath is made acid with acetic acid, and the depth of dyeing controlled by the addition of citrate of potash to the dye bath. The carmoisine red is taken up rapidly (two to five minutes), but with longer immersion the metanil yellow gradually replaces the carmoisine in the pale shades, making the required "dichroic" red-to-yellow image. These dyes can also be used in separate baths, successively, sometimes to advantage. An overdyed image can be reduced by washing, or intensified by immersion in a dye bath containing less potassium citrate.

The prints when dry can be superposed in register, and if satisfactory are fastened at one end by a strip of gummed paper, immersed for a few seconds in a tray containing amyl acetate, placed between blotters and run through a clothes-wringer to cement them together.

A more detailed explanation of the function of the dichroic image in this process follows: Taking yellow in the subject photographed, this will develop as white in the print from the panchromatic plate negative. Owing to the action of a trace of blue light in addition to the green in the green record negative, yellow will reproduce as a very pale tint, forming the thinnest parts of the gelatine relief print, which are yellow in the finished dichroic red to yellow image. Yellows (except the palest lemon yellow) are thus reproduced. The fact of having yellow so represented enables the first positive to be of a pure cyan blue or sky color.

Green is produced as follows: Light of this color photographs like black in the panchromatic plate negative and appears as cyan blue

shades in the paper print, but photographs light in the green record negative, the print from which shades to yellow in the pale tints, and combines with the cyan blue of the paper print to produce green. Thus foliage greens are well reproduced along with substantially pure cyan blue skies.

Pure reds of course present no difficulty. Oranges, which reproduce as pure white in the cyan blue print, are reproduced in the lighter middle shades of the dichroic print, and whites are absolutely clear in both images. The reproduction of neutral greys is not above criticism, but this shortcoming is seldom noticed.

Some general degradation of purity of hue might be expected, but such tendency is largely compensated for by the shortened scale of gradation of photographic plates as compared with that of human vision. This applies even in the most successful trichromatic process work, where experience has shown that strong contrasts of illumination must be avoided in order to obtain satisfactory results.

The simplified analysis and synthesis of color represented by this process was reasoned out in an attempt to arrive at a reasonably simple and cheap color motion picture process, in which both images are printed in one colloid layer,—that of the ordinary motion picture positive film; but the results were so much beyond expectation as to suggest applying the same principle in a process for prints for the album or framing.

Such limitations as this process possesses are seldom detected because they apply to colors comparatively rare and seldom of pictorial importance. These colors are cobalt blue, which reproduces as black, blue-pink which reproduces as salmon pink and some purples which reproduce as dull reds.

In general, the reproduction of hues corresponds approximately to the hues of the original objects as they would appear in incandescent lamp lighting, and the eye is satisfied.

If such a scientific compromise does not appeal to the physicist, it will nevertheless interest the psychologist, and delight the pictorial photographers who want a simplified and practical process of color photography in prints for the album or framing.

A feature of the process which will appeal to the pictorial worker is found in the fact that the surface of the finished print is a tenuous dyed graduated gelatine relief, in which colors can be locally reduced or intensified or altered with great facility by means of brush and water or dye, with perfect retention of photographic shading. At the finish, a

thin protective coating of benzole-mastic varnish is rubbed on with a pledget of absorbent cotton.

The "you press the button, we do the rest" plan has taken a great hold in this country, and many who wish to use this process will doubtless prefer to make their own negatives only, intrusting the color print making to people specially equipped for such work but still permitting of such local treatment as fancy dictates on the cemented prints, before finally applying the benzole mastic protective coating.

PHOTOGRAPHIC PLATES FOR USE IN SPECTROSCOPY AND ASTRONOMY II.*

By C. E. Kenneth Mees
[Eastman Kodak Company, Rochester, N. Y. Received January 19, 1932]

Since the preparation of the paper of this title published in the Journal of the Optical Society of America (December 1931, p. 753), further work in our research laboratory has resulted in some materials which it seems worth while to call to the attention of scientific workers.

Emulsions

In addition to the types of emulsion discussed previously, it has been found that the extremely contrasty, slow bromide emulsion, which has been used chiefly for solar photography, is very suitable for sensitizing,

Fig. 1. *Microdensitometer tracing showing the graininess of contrasty, slow bromide plate.*

especially for the infrared portion of the spectrum. This emulsion has the following characteristics:

Inertia (*i*)	$10/i$	$\gamma\infty$	S_A	$T_d(0.8\lambda\infty)$
.40 m.c.s.	25	5.0	15	3.0 mins.

Its resolving power for optimal image density with a test object contrast of 20, $\gamma = 0.80\gamma\infty$, is 85. The graininess as shown by the microphotometer is very low, as will be seen in Fig. 1.

While this material is too slow to be practically useful without color sensitizing, when it is sensitized to the red and infrared the high re-

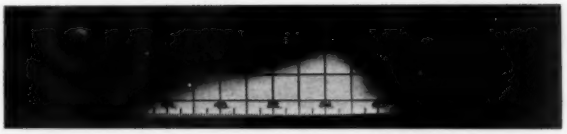

Fig. 2. *Wedge spectrogram showing Type G sensitizing.*

solving power and low graininess make it valuable wherever sufficient light is available, and this may therefore be added to the basic emulsions discussed on p. 769 of the previous paper.

Sensitizing for the Green

Several improvements have been made in the preparation of emulsions of high green sensitivity. Fig. 2 shows a method of sensitizing

* Communication No. 487 from the Kodak Research Laboratories.

(Type G) to give a very high maximum at 565 mμ. This is particularly suitable for use with refracting telescopes and yellow filters, since the distribution of spectral sensitivity corresponds approximately with that previously obtained by the orthochromatic or isochromatic type of photographic plates, while at the same time the effective speed, the keeping power of the emulsion, and the freedom from fog give it distinct advantages.

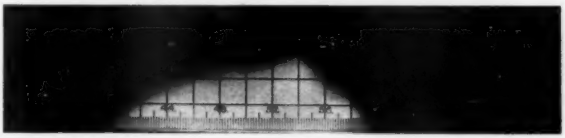

FIG. 3. *Wedge spectrogram showing Type H sensitizing.*

Another type of green sensitizing is known as Type "H" (see Fig. 3). This gives general sensitiveness throughout the green with no appreciable gap, the maximum being at 530 mμ.

Yet another method of sensitizing is employed to produce the maximum sensitiveness in the blue-green, this being particularly important

FIG. 4. *Wedge spectrogram showing Type J sensitizing.*

with contrasty emulsions, such as Type III or the new high contrast Type IV. This sensitizing, known as Type "J", is shown in Fig. 4.

For general sensitizing up to the extreme red, the Type F sensitizing

FIG. 5. *Wedge spectrogram showing Type F sensitizing, Emulsion Type III*

has now been modified to eliminate the gap in the blue-green. The new sensitizing is shown in Fig. 5 on a Type III emulsion for a tungsten light spectrum. This type of sensitizing will be seen to give a very even spectrum.

This same type of sensitizing can be applied satisfactorily to emulsion Type IV. Such a plate will have about one-eighth the sensitiveness in the red and green of a Type III emulsion but higher contrast, improved resolving power and graininess. Preliminary tests suggest that this plate may be valuable for the spectra of B and A type stars, the great contrast enhancing the visibility of the absorption lines.

As the sensitiveness extends towards the infrared, the loss of speed diminishes, so that for the infrared sensitive materials, Type IV emulsion is only about half the speed of the Type III emulsion sensitized for the same region.

A new sensitizing effect (Type "N") is shown in Fig. 6. This fills in

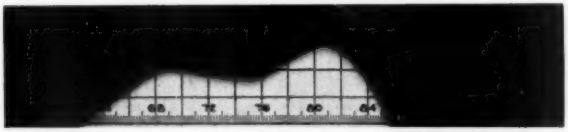

FIG. 6. *Wedge spectrogram showing Type N sensitizing.*

the gap previously existing between the visible spectrum and the infrared sensitive plates. Up to the present this can be supplied only on Type IV emulsion.

Finally, a new sensitizer has recently been obtained which gives extraordinary sensitiveness to the extreme infrared, the spectrum of

FIG. 7. *Wedge spectrogram showing Type Q sensitizing.*

which is shown in Fig. 7. This sensitizer, which has been termed "Xenocyanine," is of very complex structure and is very unstable. Special precautions are required for the handling of the plates. At the present time they can be made only by special arrangement, since the plates will not keep. The sensitizing has been termed Type "*Q*", and the plates are known as "Eastman Infrared Sensitive Plates B."

A NEW BENCH FOR TESTING PHOTOGRAPHIC LENSES

By R. Kingslake

[Institute of Applied Optics, University of Rochester, Rochester, N. Y. Received January 19, 1932]

ABSTRACT

In planning the equipment for the recently established Institute of Applied Optics at the University of Rochester, it was decided to build a photographic lens testing bench, which should be suitable both for instruction to students and for research work. A description of the construction, adjustment, and use of the bench is given in the present paper.

In designing the bench, it was decided to use a distant point source of light or other suitable test object, and to mount the lens so that it can be rotated about a vertical axis through its second nodal point, and set at any desired obliquity up to 60°. The image formed by the lens is then examined with a microscope in the usual way. It was also decided to incorporate an automatic mechanism to ensure that the focusing point of the microscope is always in the ideal flat field which the lens should have; and further, to provide such auxiliary motions as are necessary to test telephoto lenses.

Scales are provided for the direct measurement of astigmatism, curvature of field, distortion, and oblique color; and by suitable means it is also possible to determine the amount of spherical and chromatic aberration should this be required. The range of focal lengths is from 5 to 60 cms with a provision for the direct measurement of the equivalent focal length and the back focus of the lens.

The bench contains within itself adequate means for making complete adjustments of all its parts, and for correctly setting the zeros of all scales.

The paper is divided into four sections:

I Theoretical considerations
II Mechanical construction of the bench
III Adjustments of the various parts
IV Criticisms of the design.

The principle of the Nodal Slide Bench for testing photographic lenses is well known, and a considerable number of such benches have been made from time to time by various firms and laboratories. In deciding to design and construct our own bench rather than to make use of an existing type we are only following the general custom, because it usually happens that the requirements of one user are quite different from those of another. In the present instance the primary requirement was a lens testing bench that could be used to teach students the nature of the various aberrations of a photographic lens and how to measure them; at the same time it was felt desirable to construct an instrument having the necessary accuracy and elaboration for such future researches on lenses and aberrations as may be carried on in the Institute.

I. Theoretical Considerations

It can easily be proved that every centred lens system has a definite axis of rotation which crosses the axis of the lens, about which the lens may be turned through a small angle without producing any sideways

displacement of the image. A small rotation about any other axis will produce some lateral image displacement. If the object is at infinity, the axis of rotation for a stationary image passes through the second nodal point of the lens, which coincides with the second principal point if the lens is used in air as is invariably the case with photographic objectives.

This property of the second nodal point of a lens used in air suggests a simple means for measuring the focal length; for, if the object is at infinity, the image is at the focal point, and the distance from the image to the nodal point is then equal to the true equivalent focal length of the lens.

The fact that it is possible, by a suitable choice of axis of rotation, to alter the obliquity of the light passing through a lens without causing any sideways displacement of the image, has frequently been utilised for testing the lens itself. Suppose a microscope is mounted horizontally so that it can be moved backwards and forwards along its own axis, which must intersect the vertical axis of rotation of the lens about its nodal point, then the microscope can be focused on the image of a very distant object formed by the lens. A small rotation of the lens about its vertical axis will produce no sideways displacement of the image seen through the microscope. If the obliquity is now increased, the appearance of the image will gradually change because the light will be passing through the lens more and more obliquely, introducing the oblique aberrations of the lens, namely coma, astigmatism, oblique colour, and higher order aberrations, in addition to the axial aberrations which of course remain at all obliquities.

Two other aberrations will produce characteristic effects, namely curvature of field, and distortion. These must be considered separately.

CURVATURE OF FIELD

It will be seen from Fig. 1 that as the lens is tilted, its field swings round with it, making it necessary to withdraw the microscope further from the lens as the obliquity ω is increased, in order to keep the image in focus. If F represents the focal length of the lens, and N_1 and N_2 the nodal points, then the amount by which the microscope must be withdrawn if the lens has a perfectly flat field will evidently be $F\ (\sec \omega - 1)$. If the field is curved inwards or outwards from the ideal plane, the microscope must be moved respectively less or more than this amount.

DISTORTION

If a lens possesses distortion, the obliquity ω of the entering parallel rays is only the same as the obliquity ω' of the ray emerging from the

second nodal point so long as the obliquity is small; as the lens is more and more tilted, ω' becomes less than ω if barrel distortion is present, and greater than ω for cushion distortion (Fig. 2). Hence, if distortion

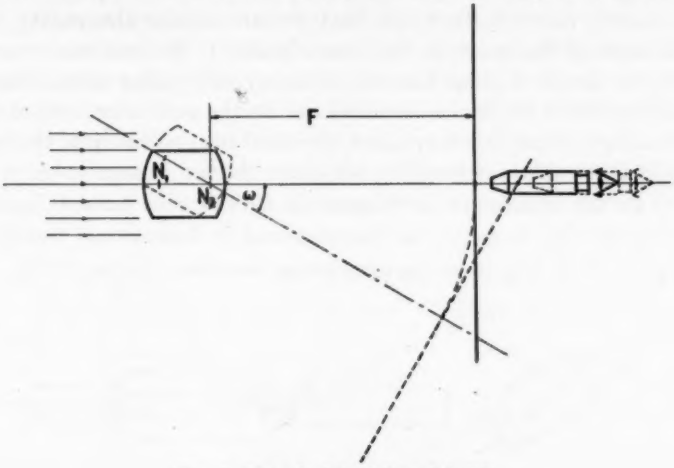

FIG. 1. *The principle of the nodal slide.*

is present, rotation of the lens about its nodal point will produce a sideways movement of the image at large obliquities, whereas no sideways motion is observed for small rotations. Thus by providing the observing

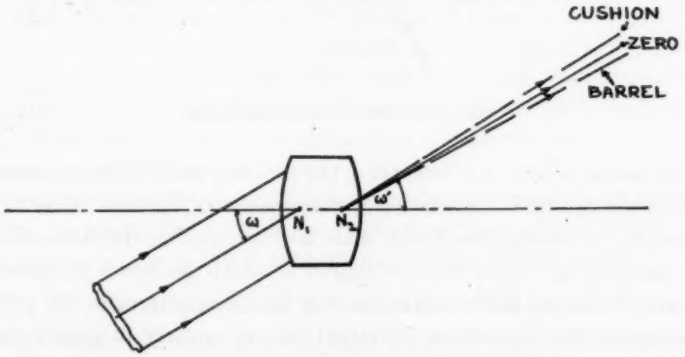

FIG. 2. *The effect of distortion on image position.*

microscope with a cross motion in addition to its longitudinal motion, we can measure distortion directly. It should be noticed that the measured sideways displacement of the image must be multiplied by sec ω to give the distortion in the ideal image plane.

AUTOMATIC FLAT-FIELD MECHANISM

Photographic lenses are usually so designed that they shall produce an image on a truly flat photographic plate. The first requirement of a lens-testing bench is, therefore, that we can examine the quality, size, and shape of the image in this image plane. If the lens has a curved field, the choice of plane becomes arbitrary, depending on the class of work for which the lens is required and on the particular type of field curvature present. In many cases, the axial image (centre of the field) should be as sharp as possible, while the oblique images (edge of the field) are left to take care of themselves. On the other hand, it is sometimes preferable to secure the best compromise focus at say two-thirds of the full field, and to let the axial image become as bad as it will.

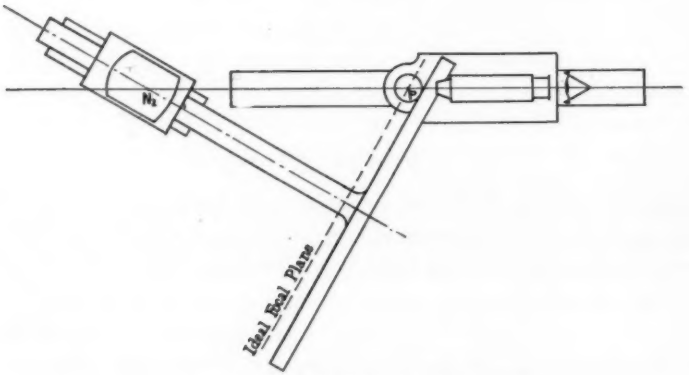

FIG. 3. *Automatic flat-field mechanism.*

In making a test on a lens, then, the focusing point of the microscope should always be in the chosen focusing plane of the lens. To save the necessity of reading the bench scale and calculating the flat-field correction $F(\sec\omega-1)$ for every obliquity at which the lens is to be tested, an automatic flat field mechanism may be incorporated. In the present instrument this consists of a straight bar, accurately perpendicular to the optical axis of the lens, against which runs a small roller attached to the front of the sliding microscope carriage, the arrangement being such that the focusing point P of the microscope (Fig. 3) is accurately in the vertical axis of the roller, and that the plane containing the vertical axes of the nodal slide and the roller shall be truly parallel to the ways

along which the microscope moves, and also parallel to the incident light.[1]

THE PROBLEM OF THE TELEPHOTO LENS

A telephoto lens, consisting essentially of a convex and a concave element separated by a finite distance, presents some difficulties when mounted on a nodal slide, because the nodal points of such a system are situated at a considerable distance in front of the convex element. Consequently, when the lens is rotated about the second nodal point N_2, the entire lens is swung off the axis of the bench, the emerging light then proceeding obliquely to the observing microscope. This is shown diagrammatically in Fig. 4.

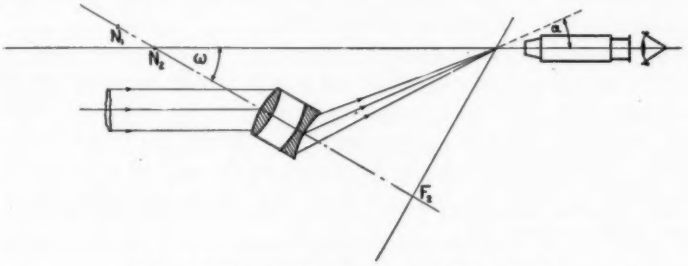

FIG. 4. *Testing a telephoto lens on a nodal-slide bench.*

T. Smith and J. S. Anderson[2] have discussed this situation, and point out that the microscope must be capable of being rotated about its focusing point through such an angle α that the emerging light from the lens will enter the microscope objective axially, this angle being determined experimentally by removing the eyepiece and looking at the back of the microscope objective to see if it is illuminated centrally by the light from the lens under test.

In determining the distortion, the measured lateral shift of the microscope perpendicular to its own axis must now be multiplied by $\sec(\omega+\alpha)$ to give the true distortion in the ideal image plane.

EFFECTS OF USING A RELATIVELY NEAR OBJECT

The foregoing theory assumes that the light entering the lens under test is truly parallel, the simplest way of securing this being to use an

[1] A similar mechanism is used in the lens testing bench made by Messrs R. and J. Beck, see Glazebrook 'Dictionary of Applied Physics' 4, p. 5; and also by Messrs Adam Hilger Ltd. in their lens testing interferometers, see Trans. Opt. Soc. *22*, 174; 1920–21 and Proc. Opt. Conv. 1926, p. 1032.

[2] Trans. Opt. Soc., *23*, 188; 1921–22.

accurately focused collimator. For focal length determinations this arrangement is ideal, but when a detailed examination is to be made of the image formed by the lens under test, the spherical and chromatic aberrations of the collimator objective, however good, become serious. For critical lens testing, then, a collimator is a thing to be avoided, although it is a very compact and convenient source of parallel light for a rough or preliminary test of a lens and for focal length measurements. Moreover, if a collimator is used for testing telephoto lenses, it must be made to give a parallel beam of light of sufficient diameter to fill the test lens at its most extreme obliquity; or alternatively, the collimator must be movable laterally at right angles to its axis, this motion being such that the collimator axis does not change its direction by the slightest amount while being moved sideways.

Unfortunately a really distant pinhole or other source of light is impossible in ordinary laboratories, and it is generally necessary to resort to the use of an object at a distance which is very far from being infinite. This case is discussed in a paper by G. W. Moffitt,[3] in which he proves that if a is the distance from the source to the axis of rotation of the nodal slide, and b is the distance from this axis to the image, then the focal length is given by

$$F=\frac{ab}{a+b}\left[1-\frac{s}{a-b}\right]$$

where s is the separation between the two axes of rotation which give a stationary image of the near object at a distance a when the lens is turned first one way round and then reversed. Clearly if s is small, as is commonly the case particularly for relatively thin systems, the focal length as determined by the usual formula

$$\frac{1}{F}=\frac{1}{a}+\frac{1}{b}, \quad \text{or} \quad F=\frac{ab}{a+b}$$

will be practically exact; but where s is considerable, the more precise formula must be used.[4]

Moffitt also points out that when using an object at a finite distance, the measured curvature of field is really that due to a spherically curved object-surface centred about the axis of rotation of the nodal

[3] J.O.S.A., *4*, 1; 1920.

[4] There are other possible sources of error to be considered here; See J. A. Tomkins *On the Nodal Slide Method of Focometry* Phil. Mag. *35*, 21; 1918.

slide, which in general cannot strictly be converted by any means into the desired value of the curvature of field for a plane object at an infinite distance from the lens unless we know the structure of the lens itself. Similarly, our measure of the distortion will not be strictly exact either, unless the ray which enters towards the first nodal point happens to be the principal ray or central ray of the entering cone of light, in which case the distortion measured will of course be that for the given object distance. However, with an object distance of say 60–100 times the focal length of the lens or more, these errors are never likely to become large.

T. Smith[5] has pointed out that a lens may be tested at finite magnification by using two T cross-bars, one for the object-point and one for the focusing-point of the microscope. Owing however to the considerable mechanical difficulties of this scheme in practice, he has suggested that a suitable auxiliary lens system could be used between a fixed near object and the lens under test, this auxiliary lens being moved along the centre-line of the bench by a link connecting it directly to the microscope carriage so that both move together. In the paper quoted, it is shown that the auxiliary lens system must be afocal, a Galilean telescope being a very convenient system for the purpose.

II. MECHANICAL CONSTRUCTION OF THE BENCH

The principles outlined above are incorporated in the bench which has been constructed in the Instrument Shop of the Institute of Applied Optics. A heavy cast-iron base (1), shown in Figs. 5 and 6, carries at one end a massive bronze bearing (17) for the nodal slide, and along its whole length two sunk steel rods (19) on which the microscope carriage (6) travels. The steel spindle (18) of the main bearing of the nodal slide carries a divided circle (22) reading to single degrees with adjustable indexes on the base casting; it also carries an overhung iron casting (2) on which slides a second casting (3) to which is bolted the lens bracket (4). Into the upper casting (3) slides the central arm of the T-shaped cross bar (5), which can be moved along relative to the lens holder by a rack and pinion (12) to alter the focus. The upper casting (3) can be moved over the lower casting (2) by the pinion (13) in order to set the lens so that its nodal point comes over the axis of the main bearing. Each of these movements is provided with a clamp. The lens bracket (4) is bored out to carry a rotatable lens-mount (20),

[5] J. Sc. Inst. *1*, 209; 1923–24.

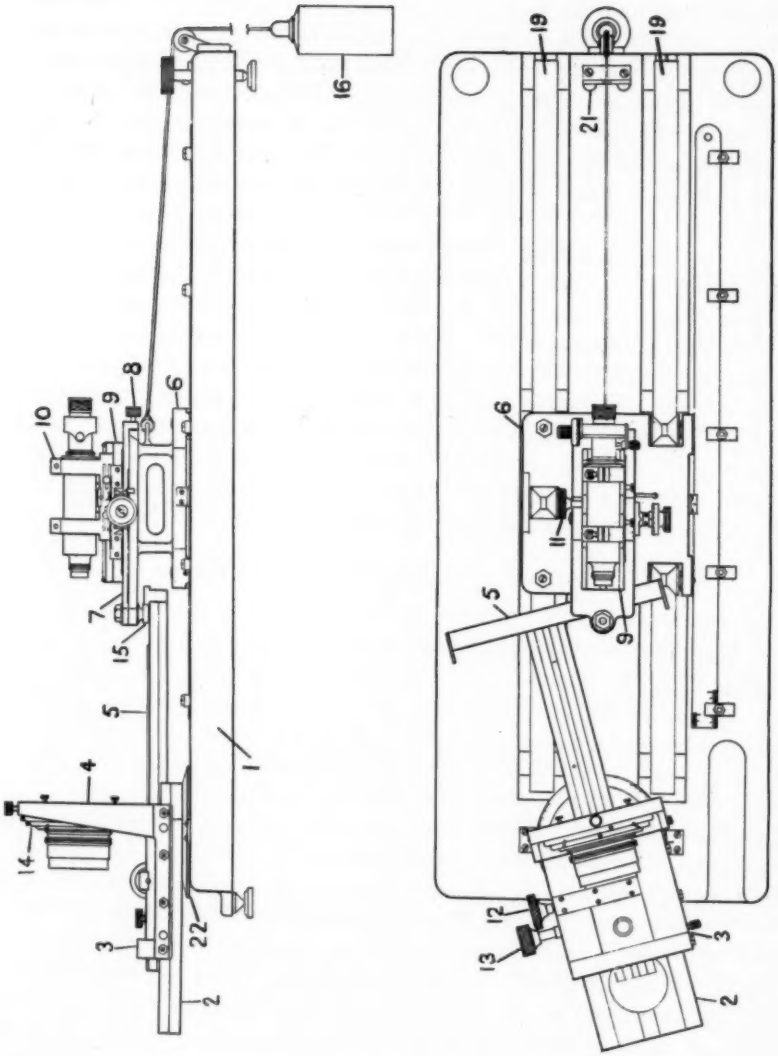

FIG. 5. *Above: Side elevation of bench, obliquity zero. Below: Plan of bench, obliquity 15°.*

the greatest care having been taken in the construction to ensure that the horizontal axis of the lens-mount rotation accurately intersects the vertical axis of the main bearing. The lens is screwed by means of suitable flanges to a pair of eccentric rings (14) turning in the lens-mount (20), by means of which the optical axis of the lens can be set to coincide with the horizontal axis of rotation of the lens mount. This method of mounting makes it possible to set the optical axis of the lens into coincidence with the centre-line[6] of the bench.

In testing telephoto lenses, it may be necessary to reverse the lower casting (2) in order to set the lens sufficiently far back from the vertical

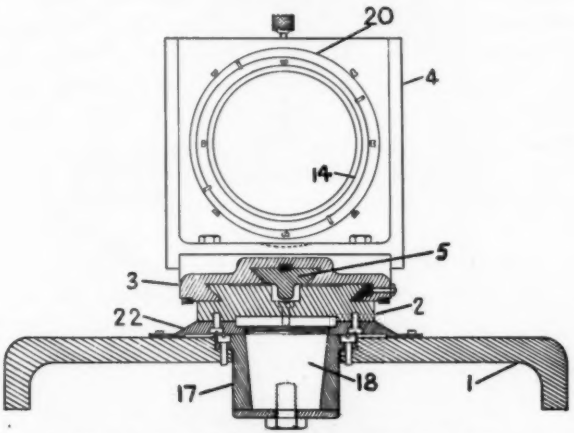

FIG. 6. *Cross section through main bearing of nodal slide.*

axis of rotation, the maximum distance from the lens flange to the nodal point which may be accommodated on the bench being 25 cms. This possibility requires that the dovetail slide between parts (2) and (3) must be very accurately constructed so that it shall be reversible without thereby introducing any lateral displacement of the upper part relative to the axis of the bearing. It is convenient, too, that the T cross-bar should be reversible without decentration because it is sometimes desirable to turn the lens holder right round and insert the cross-bar from the other end.

Turning now to the microscope carriage, this is illustrated in Figs. 5, 7, and 8. It will be seen to consist of a cast-iron carriage (6) running

[6] By this term is meant the line through the horizontal axis of rotation of the lens holder, parallel to the left-hand rod on which the microscope carriage runs.

on three V-groove rollers along the sunk steel rods (19). The two rollers on the left are pivoted on point bearings, adjustable along their length by a small amount to enable the axis of the microscope to be set accurately along the centre-line[6] of the bench; the roller on the right is allowed to run freely on a steel spindle, with enough end play to take

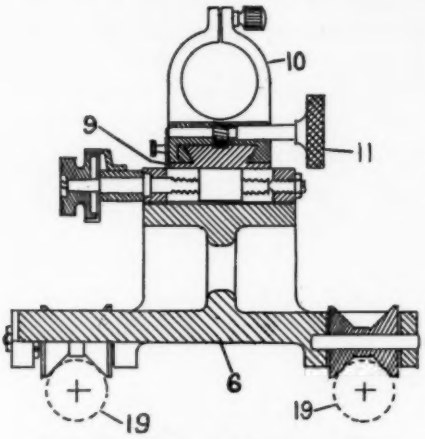

FIG. 7. *Cross section of microscope carriage.*

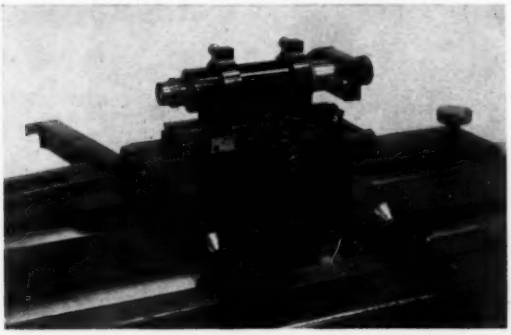

FIG. 8. *Side view of microscope carriage.*

up its own position. The diameters of the rollers were carefully adjusted so that the upper face of the casting (6) is exactly parallel to the plane containing the axes of the two rods (19) along which the microscope carriage travels.

The top surface of this carriage (6) is machined flat, the metal being

made to project in front to enable the roller (15) to run against the front edge of the cross-bar (5). This roller is a single-row ball-race, 3/4 inch diameter by 1/4 inch thick, mounted on a vertical steel spindle running up through the main carriage casting. The top of the spindle is tapered to fit into an iron plate (7) which bears smoothly on the upper surface of the carriage (6). This plate has a dropped part at the back which carries a clamp (8), and also an index window by which its angular displacement about the steel spindle may be read off a divided arc on the top of the carriage (6). On top of this plate (7) is a transverse dovetail carrying the cast-iron cross-slide (9), which itself is dovetailed longitudinally to carry the brass microscope holder (10). The cross-slide has a total movement of 25 mm and is operated by a micrometer screw of 1 mm pitch, provided with means for removing all backlash, the head of the screw being divided into 100 parts with a friction device for setting the zero correctly. Whole turns of the screw are marked by a plain millimetre scale at the end of the piece (9). The longitudinal slide is operated by rack and pinion (11), and has a total movement of 12 cms. It is fitted with a millimetre scale and a vernier reading to tenths, as is clearly shown in Fig. 8. The zero of the scale is in the middle, and the position of the vernier may be adjusted longitudinally through several millimetres in order that the zero reading may be set for use with any particular microscope objective and eyepiece. The routine for setting the zeros of these scales will be described below.

In constructing the instrument, great care was taken to ensure that the heights of the axes of lens rotator (20) and microscope above the plane containing the two rods (19) were precisely the same. The roller (15) of the microscope carriage is held in contact with the cross-bar (5) by a weight (16) attached by a flexible wire cord passing over a pulley at the end of the bench.

General views of the completed bench when set up for use are shown in Figs. 9 and 10.

III. ADJUSTMENT OF THE INSTRUMENT

It was necessary after receiving the bench from the instrument maker, to make a number of checks and adjustments. These may be summarised as follows:

(a) TO CHECK THE ACCURACY OF THE RODS AND ROLLERS SUPPORTING THE MICROSCOPE CARRIAGE

These are best checked by removing the plate (7) together with its superstructure from the microscope carriage, and placing a sensitive

spirit level on the machined upper face of the casting (6). On moving the carriage along the rods, an inch or so at a time, any lack of straightness, or departure from a true plane, of the rods will be immediately apparent, and can be rectified by suitable thin packing pieces placed under the rods at the clamping points. Errors in the bearings of the rollers may be detected by mounting a temporary autocollimating telescope in place of the microscope, and observing the image reflected

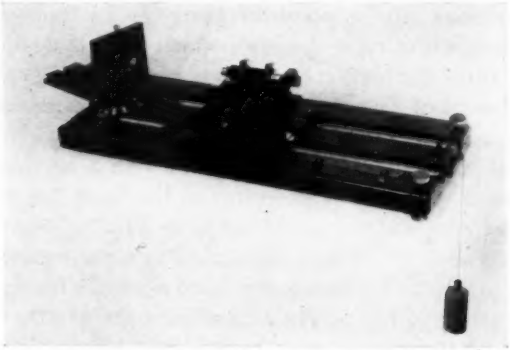

FIG. 9. *General view of bench, when testing an ordinary lens at 15° obliquity.*

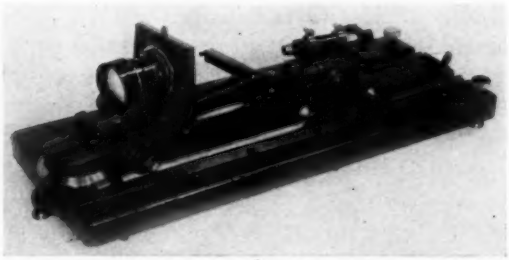

FIG. 10. *General view of bench, when testing a telephoto lens at 10° obliquity.*

from a vertical flat mirror as the carriage is moved slowly along the bench. Precision grinding must be resorted to if the rollers show any errors in this test.

(b) TO SET THE ZEROS OF THE LONGITUDINAL AND LATERAL MOVEMENTS OF THE MICROSCOPE

For this operation, the mechanism for turning the whole microscope carriage about the axis of the ball bearing roller (15) is invaluable; and

indeed it would justify the inclusion of such a mechanism even if telephoto lenses were never to be tested. The principle of the adjustment is that if the microscope, fitted with a filar micrometer eyepiece, is focused on a vertical line such as a fine scratch in a vertical silvered glass plate, which truly coincides with the axis of the roller, then on turning the microscope through 5° or so about that axis, no change in the image will be observed. On the other hand, a little consideration will show that if the vertical scratch, and hence also the focusing point of the microscope, is displaced longitudinally from the true axis of the roller, the image will move to one side in the field of view on swinging the microscope; whereas if it is displaced laterally, the image will go in and out of focus. This latter error is made easier to detect by using both a horizontal and a vertical scratch. When the microscope is turned, the horizontal scratch will appear blurred at the edges of the field, but will remain sharp at the exact position where the axis of tilt of the microscope intersects the horizontal line. Using such a silvered plate, which may conveniently be stuck with wax to a lens or metal blank screwed into the lens holder of the bench, it is a rapid and simple process to set the microscope so that its focusing point is truly over the axis of the roller. It is advisable to use a 16 mm microscope objective for this test. The two scales should then be set so as to read zero at this position.

(c) TO CHECK WHETHER THE AXIS OF ROLLER (15) INTERSECTS THE CENTRE-LINE OF THE BENCH AND TO SET THE ZERO OF THE FOCAL LENGTH SCALE

For these adjustments it is necessary to attach the ruled silvered plate previously recommended to the metal blank or lens, and to rack it forward until its vertical scratch coincides approximately with the axis of rotation of the main bearing. Movements of the scratch may then be watched through the microscope on the bench. It will be necessary to hold the microscope carriage as near to the lens holder as possible by means of a wooden strut placed between the carriage (6) and the rubber buffer (21) at the end of the bench. The T cross-bar is removed and the microscope is racked forward to focus the scratches. Then by a few trials it is possible to set the lens holder so that the image of the vertical scratch on the silvered plate as seen through the microscope remains stationary in the middle of the field of view while the nodal slide is turned about the main bearing. As before, sideways movements of the vertical scratch indicate a longitudinal displacement between the scratch and the axis of rotation; and if the part of the horizontal scratch which remains sharp at all obliquities is not in the centre, this

indicates a sideways error of the vertical scratch relative to the axis. A few trials will enable the microscope to be set with its focusing point truly over the axis of the main bearing. The microscope cross-slide micrometer should then read zero, any finite reading here indicating the precise distance by which the roller (15) is to one side of the centre-line of the bench. If this error is appreciable, it can be taken up by giving a small displacement to the front left-hand V-roller along its axis, and then repeating the adjustment. Also, at this position the main focal-length scale on the bench should be set to give the same reading as is read from the longitudinal scale of the microscope itself; in this way it is assured that the main scale gives directly the distance between the vertical axes of the cross-bar roller and of the main bearing of the nodal slide.

(d) TO SET THE INDICES OF THE OBLIQUITY CIRCLE (22)

Having made all the above adjustments, the indices can now be set by means of which the obliquity of the lens itself is read from the main circle (22). The condition here should be that the microscope carriage recedes by equal distances when the obliquity readings are the same on both sides of the centre. To make this adjustment, the T-cross-bar should be racked out by about 10 to 12 inches, and one index plate clamped to the base of the instrument at approximately the correct position. The microscope is then swung round so as to be roughly perpendicular to the centre line of the bench, and is focused on a definite mark on some external object such as a piece of metal held in a suitable clamp, the setting being made at say 20° obliquity of the nodal slide. The obliquity is then reversed, and gradually increased until the original mark returns to the X-wire of the microscope. Since at this point the obliquity is actually equal to the original obliquity, the circle index should be reset to give the mean of the two readings observed. A second trial should be made to verify the setting. The second index can then be set at once to read the same as the first on the opposite side of the circle.

The apparatus is now ready for use. The lens to be tested is screwed by a suitable flange to the centring rings on the lens holder, and the image of an artificial star or other source is focused by racking the T-bar along its length, and brought into the centre of the field of the microscope by leveling the bench as a whole and by moving it round on the table. The lens must now be centred by the eccentric rings, the test for centring being to observe whether the image moves in the field of the

microscope when the lens holder is rotated about its horizontal axis. Now the nodal point can easily be adjusted by the lower pinion so that the image remains stationary over about 2° of obliquity each side of the centre. As a check on the squaring-on of the lens, the obliquity may be set at zero, the microscope objective removed, and the reflected images in the various surfaces of the lens under test observed by means of a Cheshire 'Squaring-on Eyepiece'.[7] The lens being now in true adjustment, the test may be proceeded with as desired.

SPHERICAL ABERRATION ATTACHMENT

It is proposed to construct a convenient pair of diaphragms, one fixed, with a horizontal slot, and the other movable up and down, with a V-shaped slot, by means of which the focus for various zones of the lens may be accurately located according to the method suggested by Beck.[8] Unfortunately time has not yet allowed of the construction of this useful accessory.

IV. CRITICISMS OF THE DESIGN OF THE BENCH

As a result of many experiments with this bench, it was felt that, were another bench of the same type to be made, a number of alterations would be desirable. These are as follows:

(a) The nodal slide mechanism should be constructed in such a way that it is possible to set the cross-bar roller right over the axis of the nodal slide, in order that lenses with a focal length of 10–15 mm could be tested if desired. The present limit is about 5 cms focal length.

(b) It might be better to use plain scraped slides instead of the rod and roller mechanism for the microscope carriage.

(c) The amount of measurable rotation of the microscope about the axis of the roller should be much greater, necessitating some provision to allow the distortion micrometer head to clear the top of the carriage casting.

(d) A more universal lens holder should be provided, together with more rigid and simple means for centring the lens than the eccentric rings at present in use. Some provision should also be made to tilt the lens slightly if necessary.

(e) The cross-bar should be set lower down nearer the rods, to minimize the tilting tendency of the side force of the cross-bar at great obliquities.

[7] Trans. Opt. Soc. *22*, 235; 1920–21.
[8] Trans. Opt. Soc. *28*, 37; 1926–27.

(f) The pinion (13) for adjusting the nodal point should be mounted to the upper instead of the lower member of the slide, the rack being then mounted to the lower member. Moreover, the rack should be as central as possible to minimize twisting of the upper part relative to the lower.

(g) A simpler sideways adjustment should be provided for setting the roller of the microscope carriage truly in the centre line of the bench, the present arrangement not being altogether satisfactory.

(h) A pair of opposing screws to rotate the bench as a whole in a horizontal plane would greatly facilitate centring of the image in the field of the microscope.

(i) The rotating parts of the nodal slide should be considerably lightened, and the main bearing should be made to work stiffly enough to prevent unwanted movements or else should be provided with a suitable clamp.

In conclusion, I wish to record my thanks to the many persons who have kindly assisted with the development of this instrument, notably to Mr. G. Fassin, instructor in the Mechanical Design of Instruments at the Institute of Applied Optics, who made most of the drawings; to Mr. McVea, the instrument-maker of the Institute, who constructed the entire apparatus single-handed with great care and accuracy; and also to the designers of the Eastman Kodak and Bausch and Lomb Companies for their advice and many suggestions.

CHARACTERISTICS OF COILED FILAMENTS IN INCANDESCENT LAMPS

By Gorton R. Fonda and Arthur A. Vernon
[General Electric Company, Schenectady, N. Y. Received December 31, 1931]

Coiling tungsten filaments into the form of a helix came into use during the development of the gas-filled lamp. The effective diameter of the filament was thereby increased and the heat loss to the gas diminished to such an extent that the notable gain in efficiency of such lamps could be realized.

Even in vacuum lamps there are advantages of a coiled filament. Until a recent date straight filaments had been used, arranged in loops which were draped back and forth on widely spaced supports. The coil is a more concentrated source of light. More important yet, however, was the discovery that its use allowed, for the same life, a notable gain in efficiency over that characterizing the straight filament lamp.

This is occasion for some surprise, for the helical shape of the filament does not allow all of the selectivity in radiating properties that is characteristic of a straight tungsten filament. The combination gives rise to multiple reflection on the interior surfaces of the helix. Shackelford,[1] for instance, found that at sufficiently close pitch the radiation from the interior of a coil approximated so closely that of a black body that the emissivity of tungsten could be measured with fair accuracy by a comparison of its brightness with that from an outer surface. The presence of multiple reflection is shown by streaks of greater brightness on the interior surfaces and also on the outer edges. At the same filament temperature as a straight wire, it is apparent therefore that the coil will, on the average, yield more light per unit of radiating surface but will consume proportionately more energy because of its greater radiation in the range of longer wave length. Its efficiency will consequently be lower.

Calculations have been made on the extent of this effect in the case of a coil wound on a 400 percent mandrel and at a 150 percent pitch. Lax and Runge[2] calculated it in two ways—one depending on an experimental determination of the brightness from the inner surfaces of the coils and the other on the geometrical relation of the coils. They found that both methods agreed in showing a reduction of about 10 percent in efficiency. Holst, Lax, Oosterhuis and Pirani[3] determined the mag-

[1] Phys. Rev. *8*, 470; 1916.
[2] ZS. f. Tech. Phys. *6*, 317; 1925.
[3] ZS. f. Tech. Phys. *9*, 186; 1928.

nitude of the angular projections from different parts of a coil and their intensity of radiation and concluded that the reduction in efficiency was 6–7 percent, based on values for the light intensity as 1.31 times that of a flat tungsten surface and for the total radiation as 1.40 times greater. These values are in agreement with actual measurements on a coil of this size, whose efficiency we have found to be reduced about 9 percent.

For a further investigation of the elements that enter into the efficiency rating, we have studied coiled filaments of various design and size, but particularly those used in the 25 watt 115 volt lamp. A typical construction used in this lamp consists of a coiled filament wound on a 210 percent mandrel at a 150 percent pitch. The reduction in efficiency due to its poorer radiating characteristics we found to be 7.8 percent. On the other hand the efficiency of this lamp proved to be 5.4 percent greater than the lamp with straight filament, operated for the same life. There are, therefore, some features present in the coiled filament lamp which are of such a magnitude as to represent a gain of 13.2 percent in efficiency above that obtainable from a straight filament.

Two of these are minor ones. A larger size of wire can be used in the coil for the same wattage consumption and this accounts for a 1.0 percent gain. For another thing, the filament is supported by only 3 molybdenum supports instead of the 9 required for the straight filament. There is therefore less energy lost by cooling,[4] and a further gain of 2.2 percent results.

There remains, however, a gain of 10.0 percent to be accounted for. Our experiments, as described below, have shown that the rate of evaporation from the coiled filament is reduced by just this amount. Such an effect is to be regarded as a consequence of the deposition of tungsten vapor upon the interior surfaces of the coil. Its extent was calculated from geometrical grounds on two assumptions: (a) that the evaporation of tungsten atoms takes place in directions normal to the surface of the wire and radiating out from it, as is customary in the case of evaporation in vacuum, and (b) that all of the atoms striking adjacent turns of the helix are condensed upon their surfaces without reflection.[5] The rate of evaporation could therefore be taken as proportional to the magnitude of those angular projections within which the evaporating atoms are free to escape without colliding upon other turns in the helix. The calculations have been carried out for a variety of man-

[4] I. Langmuir, S. MacLane, K. Blodgett, Phys. Rev. *35*, 478; 1930.
[5] I. Langmuir, Phys. Rev. *8*, 149; 1916.

drel sizes and pitch and are shown graphically in the curves of Figs. 1 and 2 as well as cited in the table. The agreement with experiment is satisfactory.

The experiments dealt with two problems—the measure of the extent to which the efficiency of the coiled filament is lowered by the change in its radiating properties and the measure of its rate of evaporation. The accuracy of such measurements depends primarily on the accuracy of the determination of temperature. The use of the pyrometer on an in-

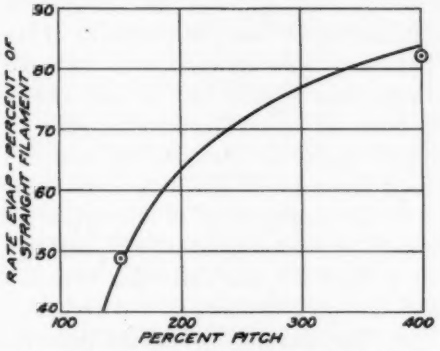

FIG. 1. *Variations in rate evaporation of coiled filaments with pitch at constant temperature and 200 percent mandrel. Curve denotes calculated values.*

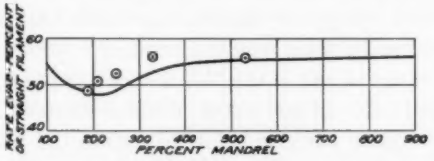

FIG. 2. *Variation in rate evaporation of coiled filaments with mandrel at constant temperature and 150 percent pitch. Curve denotes calculated values.*

candescent helix seemed liable to lead to error in the case of as small a wire as that used in the 25 watt lamp, because of the difficulty of focusing upon a part of the surface which is completely free from multiple reflection. The method of color matching with a photometer seemed preferable because the error involved is essentially very much less. For a straight tungsten filament, for instance, at 2500°K, the difference in temperature between it and a black body amounts to 250° if measured at equal brightness, but only 50° if measured at the same color.[6]

In order to have justification for this choice, preliminary measurements were made on single loops of heavy tungsten filaments, 0.51 mm

in diameter. They were first set up at constant color match and then the true tungsten temperature determined by pyrometering. The difference in temperature between coils and straight filaments was found to amount to 7° for a 150 percent pitch and to 1° for a 400 percent pitch.

In our final experiments, which were carried out on 115 volt lamps, even this error at color match was eliminated through a curious coincidence arising apparently from the use of a variable number of supports. The most reliable of our tests were carried out on one hundred and fifty 25 watt 115 volt lamps, made up for us through the courtesy of Mr. H. D. Blake of the Incandescent Lamp Department of the General Electric Company. The lamps were all made from the same spool of tungsten wire and included four types of coils as well as straight filaments. In addition to the leads, the coiled filaments had three supports and the straight nine. After bringing to constant color match, the ratio of resistance was measured between 25°C and their color temperature. After proper correction for the cooling effect of the supports, it was found to range from 13.50 to 13.58, with a mean of 13.53, corresponding to a filament temperature of 2454°K.[7] The variations were in such directions as to have no relation to style of filament. They represented an error in temperature of $\pm 3°$. The discrepancy between these results and those obtained on single loop filaments of large wire would seem to be due to the fact that the straight filament 115 volt lamp has six more supports than the coil, and consequently has more portions that are cooled. The predominance of red in them would compensate somewhat, therefore, for the predominance of red in the "blackened" radiation coming from the interior of the coils. In any event, despite whatever compensating effects may have taken place in color matching, the constancy of the resistance ratio is sufficient evidence that the tests were actually carried out at constant temperature.

The rate of evaporation was determined from measurements of both the cold and hot resistance according to the expression[8]

$$m = \sqrt{\frac{e}{\pi}}\sqrt{w_0}\,\frac{1-\sqrt{\frac{R_0}{R}}}{t}$$

where m is the rate of evaporation in grams per sq. cm per sec.

R_0 is the initial resistance

[6] W. E. Forsythe, Astrophys. J. *61*, 146; 1925.
[7] W. E. Forsythe, loc. cit.
[8] I. Langmuir, Phys. Rev. *2*, 329; 1913.

R is the resistance after a time t
e is the density of tungsten
w_0 is the weight of the filament initially.

Another group of lamps was made up in this laboratory from filaments of sufficiently larger diameter, 0.069 mm, so that the rate of evaporation could be determined from losses in weight as well as from changes in resistance. The results from both methods were in agreement.

The loss in weight at burn-out proved to be the same for all designs of coiled filaments and was equal to that found for straight filaments. This factor, therefore, does not enter as one contributing to the relative greater efficiency of the coiled filament.

A summary of the results is given in the table below. The values found for the rate of evaporation are shown graphically in Figs. 1 and 2 in order to bring out their relationship to the calculated curves. In all cases the observed values are corrected for the cooling effect so that the results as recorded apply to "ideal" filaments. Each effect is thereby segregated by itself and expressed as a specific factor, comparable with the values that have been calculated for it on theoretical grounds. In computing the operating efficiency of any lamp, the additional factors due to cooling by the supports must be considered. In the case of the 25 watt 115 volt lamp, these act to increase the relative rate of evaporation of the coils by 5.0 percent as compared with a straight filament and to increase the efficiency of the coils by 2.2 percent.

Characteristics of tungsten coiled filaments as compared with straight filaments at constant temperature

Mandrel	Pitch	Lumens per watt	Rate evap.	
			observed	calculated
Straight		100 %	100 %	
190%	150%	—	48.9	48.0
210	"	92.2	50.9	47.9
250	"	90.4	52.5	48.8
330	"	90.8	56.1	52.8
530	"	—	55.6	55.2
900	"	—	—	56.0
200	400	—	82.3	84.0
460	"	94.7	—	—
530	"	—	85.0	84.6
900	"	95.4	83.0	84.8

The importance attaching to the reduction in rate of evaporation is shown by comparing a closely coiled filament, such as that wound on a 210 percent mandrel at a 150 percent pitch, with a widely spaced one, such as that on a 900 percent mandrel and 400 percent pitch. The latter approaches more nearly a straight filament in its radiating characteristics so that its loss of efficiency on this score is less. Its rate of evaporation, however, is so little reduced, as a consequence of its more open coil, that the lamp, as compared with one made with straight filaments, has only a slight advantage, amounting to no more than 1.5 percent in efficiency for the same life. The closely coiled filament, on the other hand, gains so much more through reduction in evaporation than it loses in radiating characteristics that it can be operated at a 5.4 percent better efficiency.

In closing we would like to express our appreciation of the services of Miss Amy Walker in carrying out the photometry and life tests involved.

THE INTERPRETATION OF SPECTROGRAMS

By A. H. Taylor and T. Knowles

[Lighting Research Laboratory, Ohio. General Electric Company, Nela Park, Cleveland, Received November 16, 1931]

Spectrograms may be used in many ways to disclose facts regarding radiant energy and the characteristics of reflecting and transmitting media. Some of the most common uses are as follows:

To give *qualitative* information regarding

(a) The spectral character of the radiation from various sources, and in particular the shortest wave length radiated,

(b) The spectral transmission or reflection of various objects or materials,

(c) The spectral sensitivity of photographic emulsions.

To give *quantitative* data regarding

(d) The spectral distribution of energy from various sources of radiation,

(e) The spectral transmission or reflection-factors of various transmitting or reflecting objects or materials.

In the hands of experienced observers spectrograms yield much valuable information, but when used by careless or inexperienced observers the conclusions drawn may be very misleading.

Fairly accurate methods have been devised whereby spectrograms may be used to determine the spectral transmission-factors of various materials. The most accurate of these involve the use of a divided light beam, in one part of which is placed the material whose spectral transmission is to be determined, the intensity of the other beam being reduced by a known amount by the use of a sectored disk, optical wedge, or other means. Using a light-source which gives a continuous spectrum, or a spectrum rich in lines in the region studied, a series of paired spectrograms is made with different transmissions of the sectored disk or wedge. Upon examination of a pair some point will usually be found at which equal blackening of the plate occurs for radiation through the sectored disk and through the material. At this wave length the material has the same transmission as the sectored disk or wedge used in making the exposure.

The literature on photography is voluminous, and the factors involved in making good spectrograms are well established, but in spite of this knowledge many very important precautions are entirely overlooked or neglected by experimenters. The purpose of this paper is to emphasize some of these precautions, and to discuss some methods of observation which minimize or avoid the most obvious errors.

Some of the photographic factors affecting the density of the spec-

trographic negative are the spectral sensitivity of the emulsion, possible non-uniformity of the emulsion and the method of development. These factors are fairly well under control and need give little trouble when comparisons are confined to a single negative. Other factors of great importance are the intensity of the source, uniformity of brightness, length of exposure and the slit width. These are the factors most often carelessly handled, and when this occurs the resulting negative is of very questionable value.

At the present time the ultraviolet portion of the spectrum, especially that between λ2400 and λ3200*, is of great general interest because of its therapeutic value and the development of "artificial sunlight" lamps to supply the ultraviolet component deficient in winter sunlight. Hence this portion of the spectrum will serve to illustrate this discussion.

In order to obtain a uniformly bright source for making spectrograms it is the practice in this laboratory to place over the slit of the spectrograph a thin piece of clear fused quartz, rough ground on both sides. This avoids the necessity for accurate alignment of light-sources and results in a uniform brightness over the whole length of the slit. It also tends to integrate the energy from a source which may not be uniform in energy distribution throughout its area.

A spectrogram is of little value in the determination of the relative energy distribution of a source in different parts of the spectrum, unless there is available a similar source for which the energy distribution is known. When such a comparison source is available the spectrogram may be made to yield the desired information. Fig. 1 illustrates such a comparison, made to determine the relative amounts of ultraviolet in the region λ2800 to λ3100 for an ordinary 25-watt Mazda lamp and a 500-watt Mazda CX lamp (a high efficiency lamp with ultraviolet-transmitting bulb). The 25-watt lamp was exposed for 65 hours, the illumination at the position of the diffusing quartz being measured. On the same plate exposures to a 500-watt Mazda CX lamp varying from 2½ to 45 minutes were made, the illumination in this case being approximately double that from the 25-watt lamp. When the negative was examined it was found that the density gradient in the region λ2800 to λ3100 was steeper for the 25-watt lamp than for the 500-watt Mazda CX, due to the fact that the glass of the bulb has a steeper transmission gradient in this region, and that the energy curve for the filament of the 25-watt lamp is also steeper. This made exact comparisons impossible,

* Wave lengths in Angstroms.

but it was estimated that the 500-watt Mazda CX lamp exposure most nearly comparable with the 65 hour exposure to the 25-watt lamp was between 10 and 20 minutes. Assuming that the photographic reciprocity law (intensity × time = a constant) holds true, it is found that this particular 25-watt lamp gives approximately 1 to 1.5 percent as much ultraviolet in this spectral range as does the 500-watt Mazda CX lamp, when the illumination in footcandles is the same in both cases.

In case it is desired to compare sources differing in spectral character, e.g. mercury arcs, carbon arcs, incandescent lamps, etc., the problem

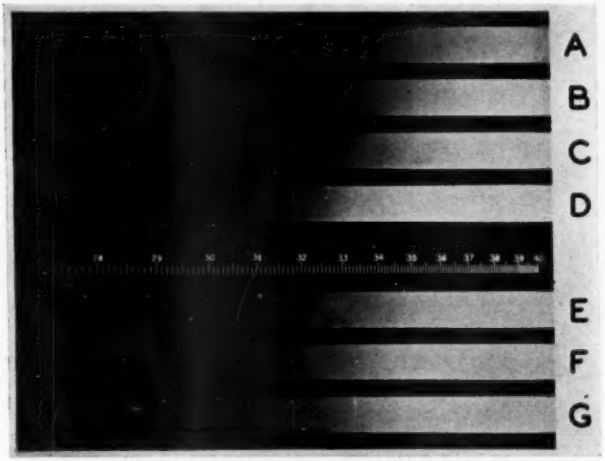

FIG. 1. *Spectrograms made with diffusing quartz before slit: D, 25-watt Mazda lamp, 65 hrs.; 500-watt Mazda CX, illumination doubled, exposed A, 2 min.; B, 5 min.; C, 10 min.; E, 20 min.; F, 30 min.; G, 45 min.*

becomes much more complex, and the spectrogram can give only *qualitative* information. Even this is frequently very misleading. Suppose, for example, it is desired to compare a quartz mercury arc, a Mazda Sunlight lamp, a Mazda CX lamp and a 500-watt projection lamp to see how they compare as to relative energy in the spectral region λ2800 to λ3100. It would appear most logical to base the comparisons on exposures at equal illumination or else equal total energy at the diffusing quartz placed over the slit of the spectrograph. Fig. 2 shows a series of exposures made under the latter condition. For each lamp a measurement was made with a thermopile to determine the relative energy at the position of the diffusing quartz. Since this was not the same for all

lamps, the exposures were timed so that the products of time and intensity of energy were the same for corresponding exposures to the various lamps. An inspection of Fig. 2 shows that very little information regarding the relative energy in the spectral region λ2800 to λ3100 can be derived from such a negative, since the sources differ so widely in their energy distribution. Much detail is lost between the original negative and a magazine reproduction, but even the negative is of little value in appraising the relative energy in definite spectral regions.

Fig. 3 shows spectrograms for three of the same lamps, exposure conditions being such that the total energy between λ2800 and λ3100 was the same for all three lamps, as determined by energy measurements

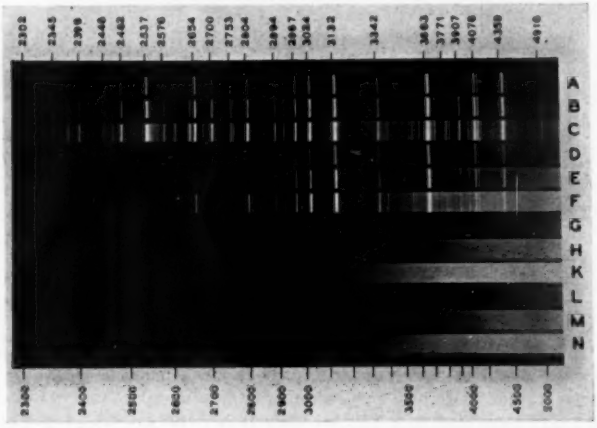

FIG. 2. *Spectrograms made with diffusing quartz before slit, equal total energy for all sources. A, B, C, quartz mercury arc; D, E, F, Mazda Sunlight lamp (Type S-1); G, H, K, 500-watt Mazda CX lamp, L, M, N, 500-watt projection lamp. Exposure-time 10 sec., 1 min., 6 min. for each source.*

with a quartz monochromator. In this figure the shortest exposure to the Mazda CX lamp shows very little blackening of the negative for wave lengths shorter than λ3000, but the corresponding exposure to the Mazda Sunlight lamp shows lines at λ2804, 2894 and 2967.

The use of spectrograms to determine the short wave-length limit of the radiation emitted by a source, or transmitted by some media such as glass, can often lead to wrong conclusions. Figs. 2 and 3 show the effect of exposure-time upon the short wave-length limit of the spectrum of each source tested. Successively longer exposures to the Mazda CX

lamp result in spectra extending farther into the short wave lengths, but finally an indefinite boundary is reached beyond which longer exposures fail to blacken the photographic plate appreciably. Very long exposures to the Mazda Sunlight lamp reveal line λ2537 or shorter, but energy measurements with physical instruments show that the energy in the lines below λ2804 is extremely small. Since the transmission of the bulb glass approaches zero asymptotically at wave lengths shorter than λ2800, very long photographic exposures reveal almost infinites-

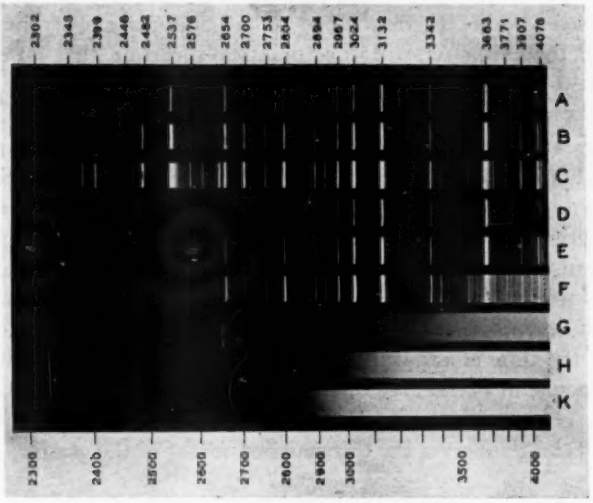

FIG. 3. *Spectrograms of quartz mercury arc, Mazda Sunlight lamp (Type S-1) and 500-watt Mazda CX lamp, equal energy at the diffusing quartz for all energy between λ2800 and λ3100. Exposures 5, 30 and 180 seconds for each source.*

imal amounts of energy, too small to be of any value or do any harm to the eyes. Hence such long exposures may lead to erroneous conclusions regarding the short-wave-length limits of such sources. Likewise, if it is desired to prove that a weak source has an appreciable amount of energy in the region λ2800 to λ3100, a dishonest experimenter can make the desired demonstration by a very long exposure.

Some rough idea as to the relative energy in the shorter wave lengths of sources such as the quartz mercury arc and the Mazda Sunlight lamp may be gained from a careful examination of a spectrogram such as is shown in Fig. 3. Long exposures or intense lines cause broadening of the lines due to reflection from the glass and diffusion in the emulsion, if

there is an appreciable amount of energy. This is especially evident for λ3024. The line λ2537 is very strong in the quartz mercury arc, and a long exposure shows almost a continuous spectrum from λ2537 to λ2576. The longest exposures of the Mazda Sunlight lamp in Figs. 2 and 3 show λ2537 very faintly.

In all of the above discussion no reference has been made to stray light. The spectrograph used in making these exposures is remarkably free from stray light. However, in many instruments stray light may apparently extend a continuous spectrum farther into the ultraviolet.

Whenever a spectrogram shows a non-uniform density across the width of the exposure strip, it is practically certain that no diffusing material was used over the slit, and that the spectrograph viewed the source directly.

Quantitative data regarding the transmission-factors of clear glasses in any definite spectral region may be obtained from spectrograms if a steady source, rich in energy in that region, is available. For example, if it is desired to determine the transmission-factor of a socalled ultraviolet transmitting window glass at λ3024, using a quartz mercury lamp as the source, an exposure to the source is made without the glass interposed and then a series of exposures is made with the glass interposed, varying the time of exposure. If one of these exposures results in the same amount of blackening of the negative at λ3024 as that obtained when no glass was interposed, the ratio of the exposure-times without and with the glass gives the transmission-factor of the glass.

SUMMARY AND CONCLUSIONS

In making spectrograms to compare different light-sources or transmitting media, the use of diffusing quartz over the slit of the spectrograph is recommended. Although the required exposures are longer, the results justify the greater expenditure of time.

Reliable methods for the determination of spectral transmission by the use of spectrograms have been developed and used by experimenters in this field.

Spectrograms may be used to obtain approximate *quantitative* data regarding the energy from sources in a definite spectral region, provided there is available a source having a *similar* energy distribution for which the energy distribution is known.

When making *qualitative* comparisons of sources having similar or dissimilar spectra, the exposures should be based on some definable con-

dition such as illumination or total radiant energy at the position of the diffusing quartz.

Spectrograms are of little value in making *quantitative* determinations of radiant energy in definite spectral regions unless similar sources of known energy distribution are available for direct comparison.

Spectrograms are often misleading when used to determine the practical wave-length limits of sources in the ultraviolet. Very long exposures or exposures at a high intensity of energy will record the presence of energy so infinitesimally small as to be undetectable by other means, hence of no practical importance. The same arguments hold true when the purpose of the test is to show the short wave-length transmission limit of transmitting media. Thickness of the specimen tested should always be stated.

ANNUAL REPORT OF THE SECRETARY OF THE OPTICAL SOCIETY OF AMERICA FOR THE CALENDAR YEAR 1931

MEMBERSHIP RECORD
JANUARY 1, 1931 TO JANUARY 1, 1932

	Honorary	*Regular Annual Payment*	*Regular Life Payment*	*Associate Individual Annual Payment*	*Associate Corporation*	*Total*
Membership as of Record in the books of the Secretary and Treasurer 1–1–31	6*	426	8	239	15	694
Died in 1930, not reported until 1931				1		1–
Resigned 12–31–29 (Not previously recorded)		1				1–
Membership as of January 1, 1931	6*	425	8	238	15	692
Gains during 1931						
By election during 1931 as of 1–1–31	0	0	0	29	0	29+
Losses during 1931						
By death	2	2	0	1	0	5–
By resignation as of 1–1–31	0	1	0	5	0	6–
By separation for non-payment of dues	0	6	0	6	0	12–
Membership as of record 12–31–31	4*	416	8	255	15	698
Gains between 12–31–31 and 1–1–32						
By election during 1931 as of 1–1–32	0	0	0	12	0	12+
By transfer 10–21–31 as of 1–1–32	0	13	0	0	0	13+
Losses between 12–31–31 and 1–1–32						
By transfer 10–21–31 as of 1–1–32	0	0	0	13	0	13–
By resignation during 1931 as of 12–31–31	0	9	0	5	2	16–
Membership as of record 1–1–32	4*	420	8	249	13	694*
Counted twice*						1–
						693

* Frank Twyman, President of the Optical Society, London, is a regular member and ex-officio honorary member during his term of office.

Died in 1930 not reported until 1931

Frank E. Howard (654 A)

Resigned as of December 31, 1929 (not previously recorded)

T. Smith (89 R)

Elected during 1931 as of January 1, 1931

Henry A. Barton (899 R)
Harry Clifford Bates (868 R)
Brooks A. Brice (882 A)
John Philip Elting (886 A)
Richard Evans (887 A)
Carl E. Foss (878 A)
M. E. Graber (871 A)
Lawrence Harris (884 A)

Louis Harris (883 A)
H. J. C. Ireton (875 R)
Ratje C. Jacobsen (873 A)
Ellis A. Johnson (885 A)
Richard N. Jones (874 A)
William J. Kroeger (880 A)
Harvey B. Lemon (872 R)
George A. Mitchell (901 A)
Donald R. Morey (889 A)
Ernest Petry (897 A)
Charles W. Rankin (890 A)
Shirleigh Silverman (879 R)
Eastman Smith (892 A)
Oscar Steiner (891 A)
Alfred M. Taylor (877 R)
Frederick A. Tompkins (881 A)
William C. Vaeth (869 A)
Milton L. Wiedmann (888 A)
Mary Elizabeth Warga (893 A)
Jay W. Woodrow (870 R)
Reynold K. Young (876 R)

Elected during 1931 as of January 1, 1932

James Barnes (894 R)
Victor E. Carbonara (895 A)
H. W. Cleveland (902 A)
John I. Crabtree (908 A)
John W. Forrest (900 A)
John Clifton Garman (907 A)
Paul R. Gleason (903 A)
Seikichi Jimbo (906 A)
Otto Oldenberg (904 A)
Forrest Clifford Shaffer (898 A)
Scott W. Smith (896 A)
Remsen V. Wood (905 A)

Elected to Regular Membership by Action of the Council, October 21, 1931, Effective January 1, 1932

James Barnes (894 R)
Henry A. Barton (899 R)
Harry Clifford Bates (868 R)
Harold F. Bennett (829 R)
H. J. C. Ireton (875 R)
Harvey B. Lemon (872 R)
Aaron Levin (866 R)
Herman E. Seemann (778 R)
Shirleigh Silverman (879 R)
Alfred M. Taylor (877 R)
Dayton Ulrey (867 R)
Jay W. Woodrow (870 R)
Reynold K. Young (876 R)

Deaths during 1931

Emily Howson (773 A)
A. A. Michelson (331 H)
A. J. Newton (40 R)
James F. Skogland (606 R)
S. W. Stratton (332 H)

Resignations during 1931 as of January 1, 1931

Ben J. Campbell (626 A)
Henry Green (103 R)
D. D. Laun (442 A)
H. W. Moody (524 A)
B. V. Storr (456 A)
Jean I. Storke (644 A)

Resignations during 1931 as of December 31, 1931

C. F. Eyring (782 A)
William C. Geer (767 R)
George H. Hamilton (709 R)
Marie A. Hinrichs (695 A)
Samuel O. Hoffman (724 A)
Henry D. Hubbard (347 R)
Leeds and Northrup (223 AC)
George D. Macbeth (45 R)
Walter E. Mathewson (713 R)
National Lead Company (655 AC)
W. W. Nicholas (617 R)
Conrad K. Rizer (429 A)
Ancel St. John (788 R)
Elbert M. Shelton (864 A)
Chester Snow (518 R)
Philip V. Wells (85 R)

(Signed) L. B. TUCKERMAN,
Secretary.

High-Voltage Transformers for X-ray Work—Two high-voltage transformers of new design, intended for operating the Lauritsen x-ray tube for cancer research in the Kellogg Radiological Laboratory of California Institute of Technology, have been built by the General Electric Company at Pittsfield, Mass. One unit has been shipped and the second is nearly completed. Each has a rated capacity of 0.03 ampere at 700,000 volts effective to ground continuously. They are intended for operation in series with neutral grounded, giving 1,400,000 volts effective, or 2,000,000 crest volts, at the x-ray tube. This is sufficient to produce x-rays at a frequency and penetration comparable to those from radium.

The transformers resemble large high-voltage terminals, in effect being built within the insulating casing of 700,000-volt terminals, each one consisting of a stack of five 140,000-volt units.

The casings are 33 inches in outside diameter, and the total height is 12 feet, 8 inches. They are believed to be much smaller for the voltage than anything heretofore built. Cooling is by three fans on the floor, the air-blast being directed at the casing and the spun-aluminum cap which radiates most of the heat and also serves as an expansion reservoir for the oil.

These transformers are of the fully-shielded non-resonating type. They have withstood extremely severe over-voltage and high frequency tests.